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DAVID W. TAYLOR NAVAL SHIP
RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

FIBER OPTIC DAMAGE ASSESSMENT SYSTEM FOR FIBER

REINFORCED PLASTIC COMPOSITE STRUCTURES*

by

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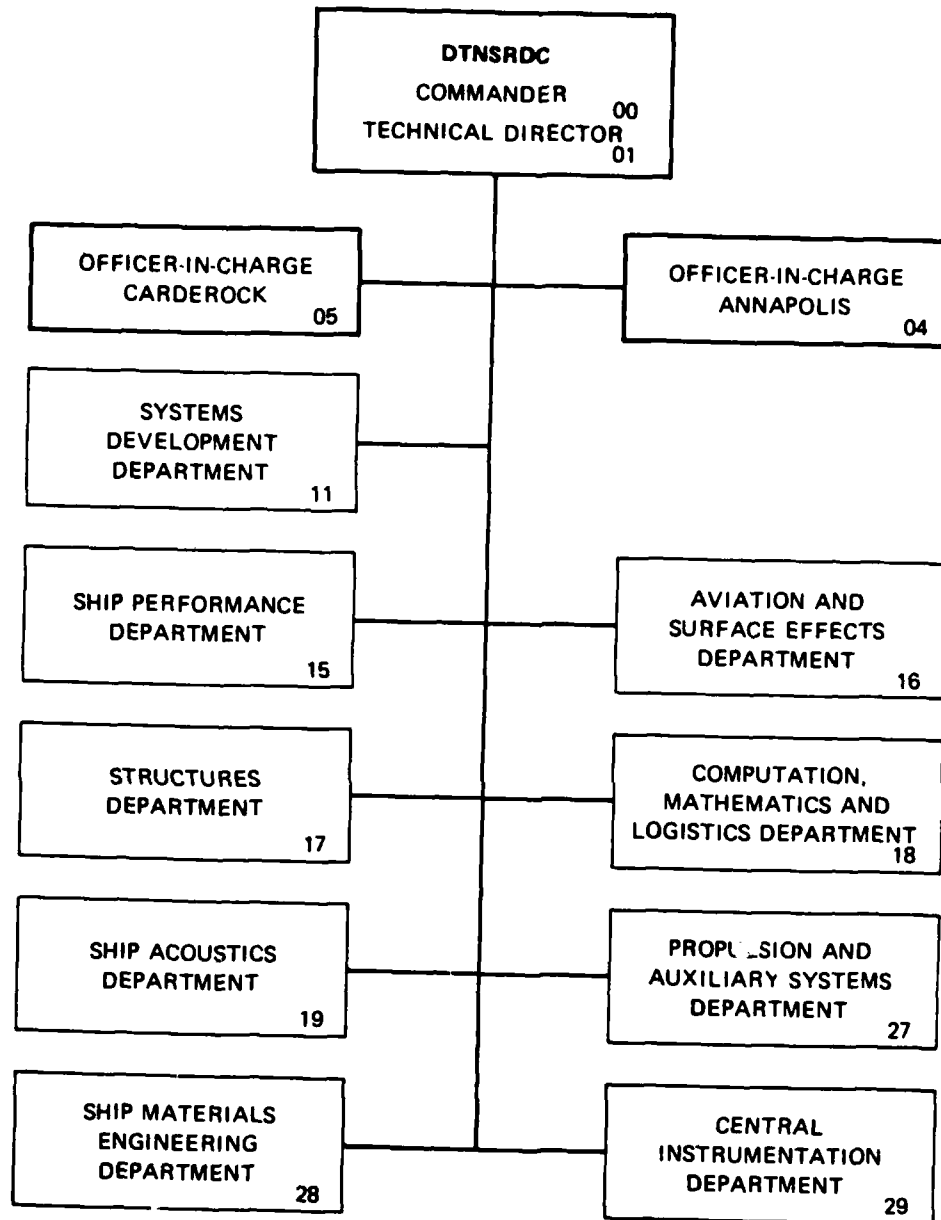Naval Sea Systems Command
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There are a limited number of nondestructive evaluation techniques available for field inspection of large composite structures and practically no viable techniques for in-service inspection. With this in mind, an innovative Damage Assessment System is proposed which is based on a concept of using an optical fiber mesh, implanted into the body of a fiber reinforced composite structure. Such a mesh would become an

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'integral part of the structure during the course of its fabrication.
The selection of the mesh fibers would be predicated on their strain
to failure characteristics and strain compatibility with the base
composite reinforcing fibers. This optical system will be capable
of locating damage, assessing severity and monitoring damage growth.
A successful implementation of the total Damage Assessment System
would involve the interaction of the optical fiber mesh with an
adequately designed interrogative electronic package. This report
focuses on the former aspect of the total system. It will address
some recent experimental work showing the practicality of the
concept in assessing various modes of failure due to impact of
composite plates, optical fiber selection, location and spacing of
fibers, as well as the utility of the system for damage assessment
in large, complex composite structures.

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LIST OF ABBREVIATIONS

DAS	Damage assessment system
DTNSRDC	David W. Taylor Naval Ship Research and Development Center
ft	Feet
ft-lb	Foot-pound
GRP	Glass reinforced plastic
in	Inch
ksi	Thousand pounds per square inch
mm	Millimeter
NDE	Nondestructive evaluation
UT	Ultrasonic testing
μm	Micrometer

ABSTRACT

There are a limited number of nondestructive
evaluation techniques available for field inspection
of large composite structures and practically no
viable techniques for in-service inspection. With
this in mind, an innovative Damage Assessment System
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due to impact of composite plates, optical fiber
selection, location and spacing of fibers, as well
as the utility of the system for damage assessment
in large, complex composite structures.

ADMINISTRATIVE INFORMATION

INTRODUCTION

The increasing use of fiber reinforced advanced composite materials for
structural applications is attributed to their attractive material properties
as well as the continuing improvement in their service performance. The
structures being replaced by composites are generally weight critical, and

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*Definitions of abbreviations appear on page iv

as such, composites with a high strength and stiffness to weight ratio provide
the impetus for their usage. This is evident in both the commercial and
military aircraft industry. In other applications, the driver may not only
be the weight advantage, but as in the case of the Navy glass reinforced
plastic (GRP) submarine sonar dome, use is predicated on acoustic performance.
In the case of the GRP sonar dome and other composite structures of considerable
size, the large projected surface area becomes especially prone to various
conditions of mechanical damage. To ensure continued structural integrity,
it is necessary to nondestructively inspect the fabricated structures
before installation and subsequently during their service life. Presently,
nondestructive inspection in the field environment is very time consuming
and can only be performed after the vessel has ceased normal operation.

This paper discusses the concept of a new nondestructive evaluation
(NDE) technique currently under consideration at DTNSRDC. It deals with the
incorporation of an optical fiber mesh at various locations throughout a composite
structure to locate damage and assess its severity in real time. Preliminary
test results on the feasibility of this concept are also presented.

BACKGROUND

Structures fabricated from fiber reinforced composite materials generally
consist of a laminated construction. The fabrication consists of laying ply
upon ply of prepreg material of various patterns and fiber orientations to
build up a specific thickness and shape. The composite design incorporates
such considerations as modulus and strength capable of supporting a particular
type of section loading. If the loading exceeds the composite strength, the
fibers in the material will usually fail or individual plies will delaminate.
For purpose of illustration, consider the case of a laminated composite structure

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subjected to an impact load. Impacting the structure normal to the plane of the material may result in noticeable damage on the compression side of the material. This type of damage may appear to be a confined area of crushed or delaminated material depending on the level of impact energy. However, most of the damage that occurs, which is not readily evident when viewed from the impacted surface is on the tensile surface in the form of gross delaminations and actual fiber breakage. Therefore, if the composite laminate face is viewed only from the impact side, even the most severe impact can at times remain visually undetected. It is possible that field inspection of a simple composite structure can be accomplished with manually held ultrasonic pulse-echo or automatic scanning units. For very large complex structures such as submarine GRP sonar domes, automatic scanning is not feasible and using hand held ultrasonic (UT) units for mapping of the entire structure will be very costly and time consuming. This inspection procedure becomes impractical when the examination must occur at sea. Since there is a real concern for the in-service survivability of GRP sonar domes as they are prone to damage from massive foreign object impact, this is the mode of damage initiation which will be used to illustrate the optical fiber Damage Assessment System (DAS) concept.

CONCEPT

Consider a rectangular section of a laminated material as representing a section of a larger structure. The impact load on the laminated structure will introduce a degree of damage at the point of impact and to the face opposite the impact site. The damage observed at high impact energy levels will manifest itself as a compressive failure or crushing at the impact site and a tensile failure on the opposite face.

The type of failure to be detected, dictates the positioning of the optical

fiber mesh. For this case, two orthogonally oriented sets of optical fibers

will be used, one near each surface of the plate (Figure 1). The two sets of

orthogonally oriented fibers will be nested within the laminae or plies of com-

posite material during the fabrication process. The grid density or spacing of

the optical fibers in a mesh can be designed to allow for more or less sensitivity

depending on expected load conditions and resulting damage in various areas of the

structure. It is anticipated that for large structures a dense grid represented

by 1/2-in. fiber spacing should suffice in the highly loaded areas prone to damage

while a looser grid of 1-in. would probably be adequate for the lightly loaded

areas less likely to see damage.

The optical fibers could be implanted in the composite body in either of two

ways. The fibers could be positioned on a prepreg lamina as the material is being

layed up or the optical fibers could be spooled and positioned in a prepreg during

its processing. The latter approach may facilitate the lamination process in the

fabrication of the structure.

The type of optical fiber implanted in the structure is dependent on the

expected strain to failure of the composite fibers. This is an important

consideration as optical fiber strain to failure has to correspond to composite

fiber failure in order for optical fibers to detect damage. With the variety

of fibers currently available, ranging in composition from glass to plastic,

appropriate selections can be readily made.

After the structure is fabricated, optoelectronics consisting of a light

source and a set of photodetectors would be integrated with the optical mesh.

The light source can be a simple light emitting diode or a more sophisticated

light emitter such as a laser. One light source can be used to illuminate a

grid of optical fibers which may be terminated in a bundle. A detector is
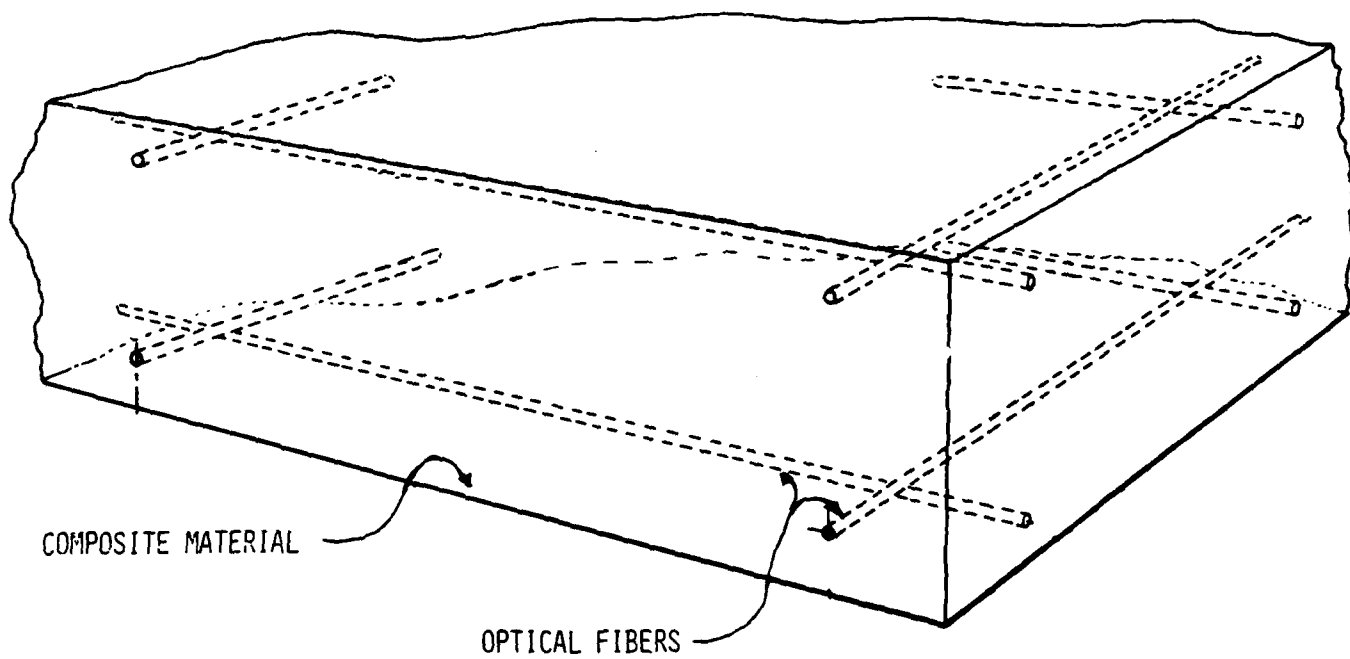
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COMPOSITE MATERIAL

OPTICAL FIBERS

FIGURE 1:   SCHEMATIC OF A SIMPLE OPTICAL FIBER MESH USED
FOR IMPACT TESTING

necessary for each optical fiber in order to distinguish which fiber has failed. For visible output, detectors will be interfaced with a cathode ray tube viewing screen such that the position of the optical fibers within a pictured structure can be displayed.

Figure 2 illustrates a drawing of a panel which was impacted at its center. If the impact was severe, causing composite fiber failure, the optical fibers should likewise fail and prevent passage of light through the fiber. The detectors, sensing this condition would display this on a viewing screen, showing the location of the broken fibers within the structure. Since fibers are positioned in an orthogonal array, the location of the damaged area is known, being the intersection of the broken optical fibers. Hence, the system is capable of locating the damage and indicates severity as function of area and depth due to the placement of optical grids at various planes in the thickness of the composite. With incipient fiber breakage, the system would appear to be no longer operative. However, this is not the case as damage growth can still be monitored on a continuing basis since adjacent composite fibers would continue to fail thus resulting in additional optical fiber failure.

The damage assessment system application should excel in structures possessing complex geometries. For composite structures with compound curvatures and varying thicknesses in two or more directions, nondestructive detectability of flaws or anomalies is generally severely reduced. The optical fiber mesh however could be utilized with confidence as its operation is not affected by the structures' complexity. A composite propeller, which appears to be a real possibility as indicated by an ongoing feasibility study, is a good examplee of a complex structure. Both radiography and UT C-scan were used to
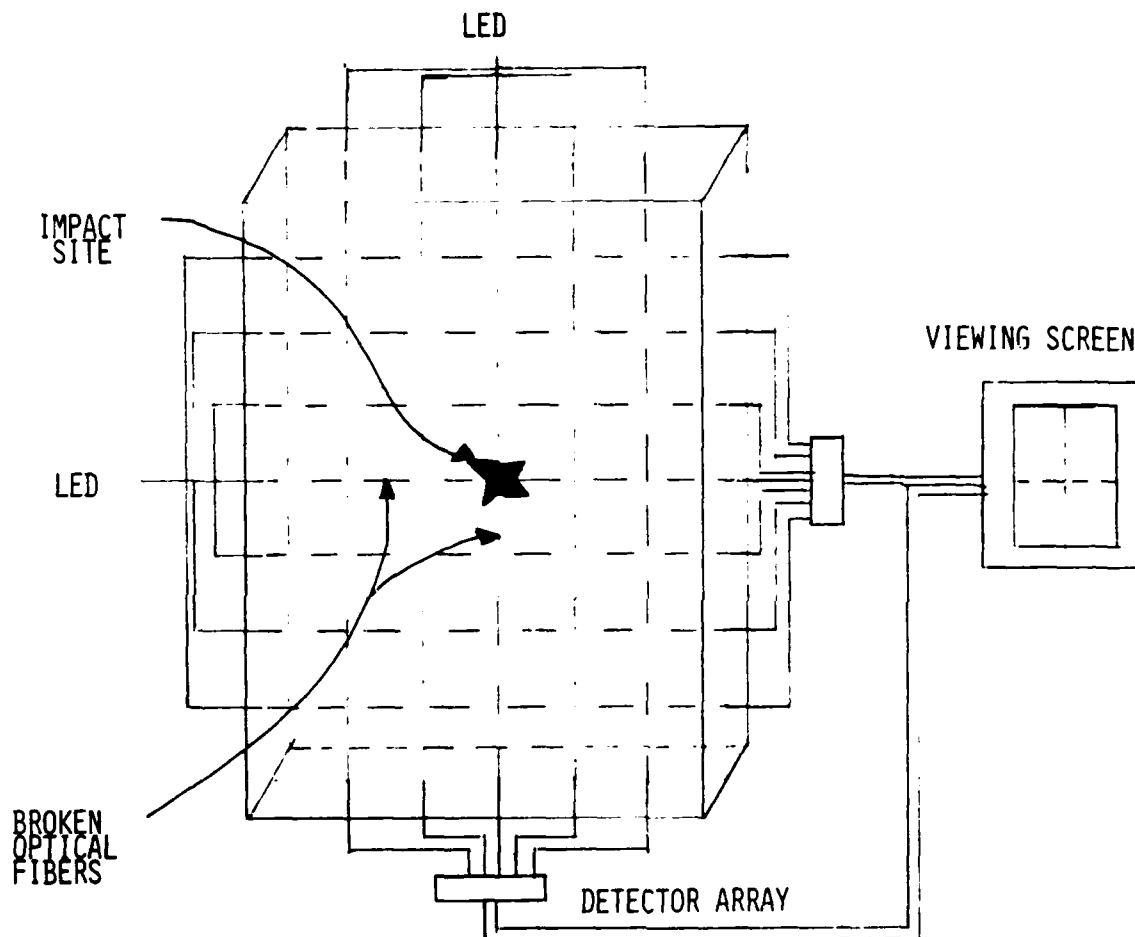
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LED

IMPACT
SITE

VIEWING SCREEN

LED

BROKEN
OPTICAL
FIBERS

DETECTOR ARRAY

Figure 2:   Schematic Of An Optical Fiber System In a Composite
Plate Showing Impact Damage

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examine the composite propeller with little information obtained due to its complex geometry. The optical fiber damage assessment system would appear to be a suitable candidate for implementation in this structure.

CONCEPT VERIFICATION

To demonstrate whether the concept is viable and deserving of further investigation and development, composite panels were fabricated containing an optical fiber mesh.

The optical fiber used throughout the experimental investigation is a Corning Glass multimode double window fiber, glass code number 1516. This is a silica glass fiber having a core diameter of 50 μm, cladding diameter of 125 μm and a total diameter with coating of 250 μm. The manufacturer has reportedly proof tested these fibers to 50 ksi with a corresponding strain of 0.5% (probable failure strain is 3.0%). It should be noted that the coating on the fiber not only acts to protect the fiber in handling but also acts to improve the interfacial bond to the epoxy resin of the composite.

Two different composite prepreg materials were used in the investigation: (1) Narmco T-300/5208 unidirectional graphite/epoxy prepreg; and (2) Hexcel 7781 E-glass fabric/F-155 epoxy prepreg.

The Narmco material consists of a Union Carbide Thornel 300 graphite fiber with 3000 filaments per tow. The graphite fiber is impregnated with an amine-cured epoxy resin having a Narmco designation 5208. The panels fabricated with this material were 3/16- x 6- x 6-in., consisting of a total of 40 plies with the following stacking designation, $[(0/90)_{10}]_s$. Three orthogonal sets of optical fibers were positioned at various depths in the laminated structure. This was done in an attempt to view damage progression throughout the laminate

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after the impact loading. The optical fibers were placed on the 6th, 7th, 21st, 22nd, 33rd, 34th plies respectively parallel to the fibers in the laminate at a 1/2-in. spacing. A schematic of the fiber positions is given in Figure 3. With the optical fibers in place, the panels were processed using a vacuum bag/ autoclave cure cycle suggested by the manufacturer.

The Hexcel material is an E-glass, eight harness satin fabric impregnated with an epoxy resin. Three different composite/optical fiber geometries were fabricated. All panels were either 1/8- or 1/4- x 6- x 6-in.. The optical fibers were placed in each direction at 1/2-in. spacing for a distance of 2-in. from each edge of the specimen. The center region of the panel, measuring 2- x 2-in., had optical fibers spaced 1/4-in. apart. This closer spacing was used to obtain a more positive indication of the damaged region due to more optical fiber failures. A top view of the fiber spacing is shown in Figure 4. The first panel with the fabric arranged in a 0/90 orientation consisted of 13 laminae and was approximately 1/8-in. thick. Optical fibers were placed on plies 3, 6 and 10 in the 0° direction and 4, 7, and 9 in the 90° direction. The second panel consisted of 26 plies having optical fibers on plies 3, 6, 10 16, 19, and 23 in the 0° direction and 4, 7, 9, 17, 20, 22 in the 90° direction. This panel was approximately 1/4-in. in thickness. The third panel consisted of 25 plies of prepreg fabric with optical fibers on plies 5, 12, and 20 in the 0° direction and on plies 6, 13, and 19 in the 90° direction again with a laminate thickness of approximately 1/4-in. The same curing procedure was applied to this material as to the Narmco material.
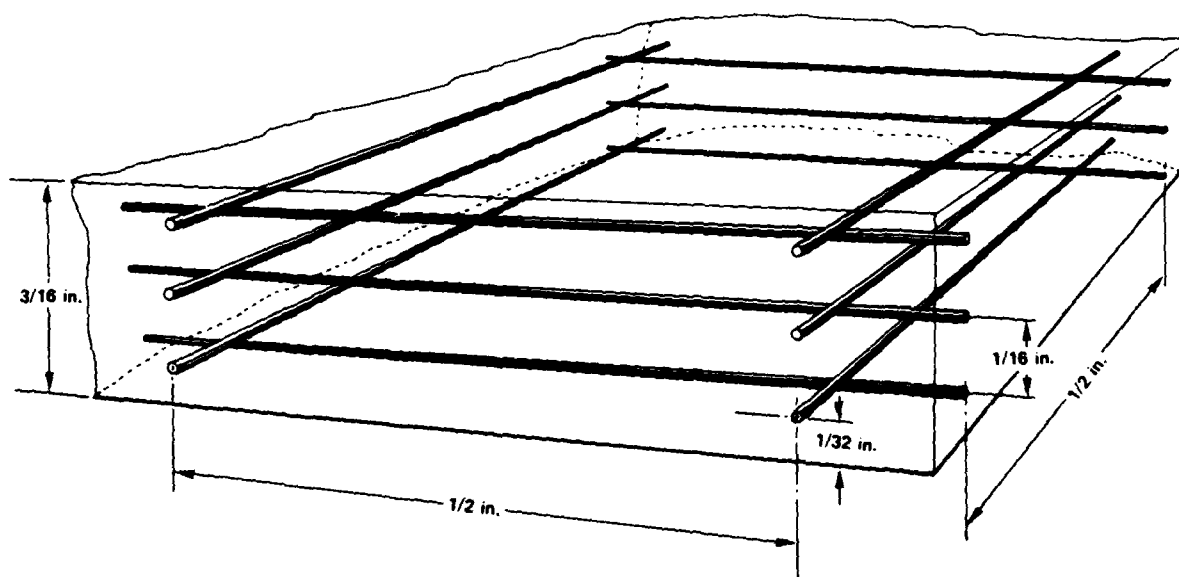
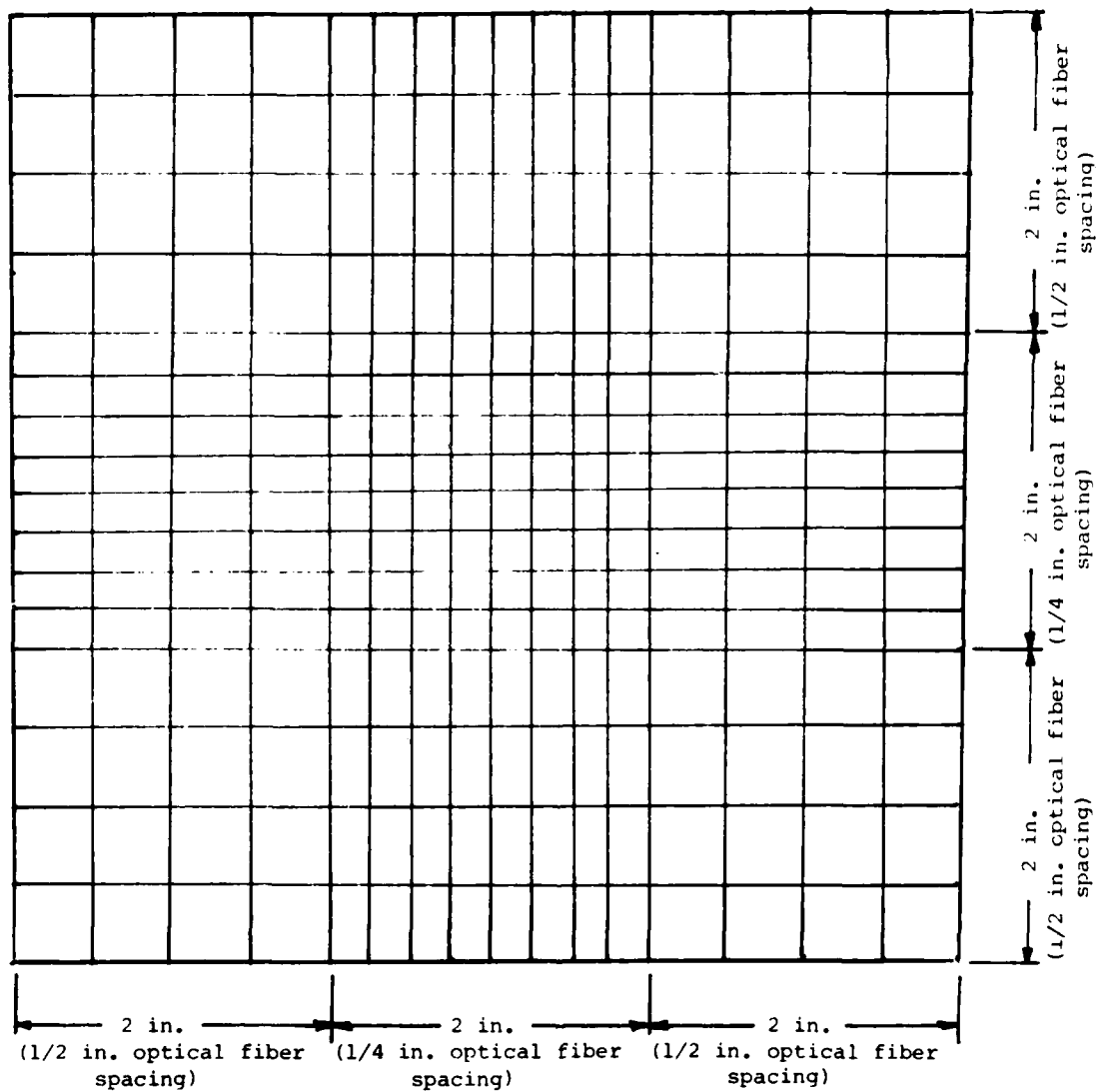Figure 3: Narmco T-300/5208 Optical Fiber Schematic

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Figure 4 - Optical Fiber Mesh Spacing For Hexcel F-155 Panels (top view)
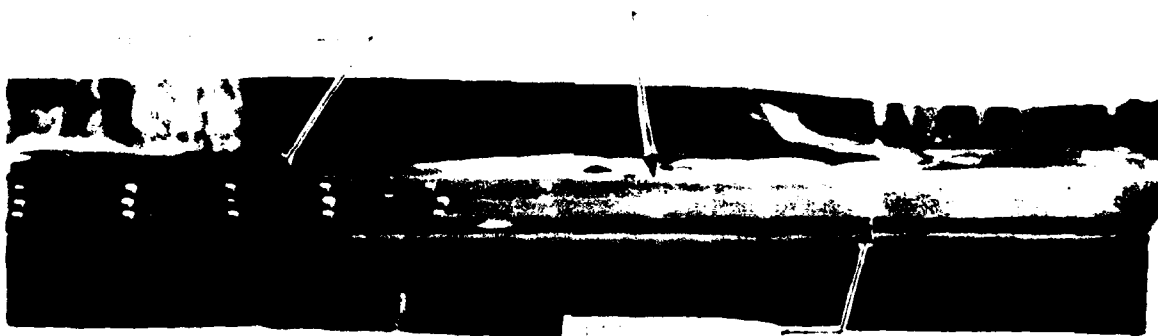
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Figure 5 - End View of Graphite/Epoxy Impact Panel With Optical
Fibers in the Thickness of the Panel to Locate
Composite Panel Damage

The edges of each panel were cut with a diamond wheel to avoid smearing of optical fiber ends with the epoxy matrix. A trapezoidal viewing box was fabricated to contain one end of a laminate plate. To determine light continuity, the panel was inserted into the box and viewed in a dark room. The light source was a standard 15 watt light bulb. This was shown to be of sufficient power for light transmission through the imbedded fibers. An end view of a typical panel is shown in Figure 5. The dark rectangular section in the picture center is the panel itself with the light colored object being the holding apparatus. The white circles on the panel are the illuminated optical fiber ends. The positions of the optical fibers are easily visible. The picture was taken in a darkened room with an ordinary 35mm camera.

The impact testing was carried out using a drop ball impact machine. To vary impact energies the drop ball height and ball size were varied. Initial testing was on panels fully clamped on four edges with a 4- x 4-in. unsupported test section. To establish an energy level that would cause catastrophic failure in the test plate, a panel of each material type was tested at different energy levels. The objective was to determine if spurious indications would be given by the optical fibers before damage was actually induced, since the energy level required to cause damage in the panels was not known. It should be noted that under these conditions of initial testing the optical fibers did not fail at any of the energy levels chosen. Damage to the composite material however did occur.

It was considered that the test condition did not allow the composite to deflect sufficiently to cause optical fiber damage. To test this premise, a glass panel was reduced in width to measure 3- x 6-in. The end constraints were then changed to two clamped edges with an unsupported test section of 3- x 4-in. The panel was impacted with 25.8 ft-lb of energy. Under these test conditions,

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the 0° and 90° optical fibers near the tensile surface failed within the damaged
location of the composite. It would thus appear that the fully clamped end
condition was not allowing adequate deflection of the unsupported span to obtain
optical fiber failure.

Other Hexcel panels were impacted and the results are given in Table 1. Each
panel that was impacted showed that the damaged area corresponded to the failure
of an optical fiber pair beneath the impact site. In all cases, the optical fibers
nearest the tensile surface of the plate failed. This result is very promising
since the system has not been optimized as to optical fiber choice.

Since the optical fibers in the glass panels functioned in the desired manner
using the 3- x 4-in test section, the graphite/epoxy panels were tested using this
same configuration. The results of the tests are given in Table 2. The damage
assessment behavior of the optical fibers in the graphite composite panels was
generally similar to that found in the glass composite panel. The less precisely
defined damaged area location by the optical fiber mesh in the graphite panels is
attributed to the failure strain incompatibility of the optical and graphite fiber

CONCLUSION

The use of optical fibers in a composite material damage assessment system
is a promising area in need of further investigation. With the limited test
results obtained it appears that the system is capable of detecting and locating
severe damage to composite materials subjected to impact loading. This system
holds promise of eliminating both operator bias and guesswork as to the extent
of incurred damage.

Future areas to be investigated include optical fiber selection and
optimization, appropriate fiber spacing for particular loadings and structures,
emitter and detector selection and interfacing instrumentation.

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TABLE 1 - HEXCEL E-GLASS IMPACT TESTS

Specimen (in)	Drop Height (ft)	Ball Dia (in)	Weight (lb)	Impact Energy (ft-lb)	Observation
1/8 x 3 x 6	6.5	3	3.96	25.8	Optical fiber damage in 6-in. direction only; location offset from panel center but at the visually most damaged area. Panel had delamination on tensile surface with minimal fiber breakage off center. Panel damage confined to side on which optical fiber failed.
1/8 x 3 x 6	7.5	3	3.96	29.7	Optical fibers failed in both directions indicating damage at site. Panel tensile surface had delamination but no fiber breakage Viewing from compression surface indicates little damage, only slight discoloration
1/4 x 3 x 6	5	4.5	13.43	67.0	Optical fibers failed in both directions, locating impact site. Panel showed delamination over entire test section with no fiber breakage.
1/4 x 3 x 6	5.5	4.5	13.43	73.1	Optical fiber failed in both directions, 1/2-in. offset from impact site. Panel showed delamination over entire test section with no fiber breakage.

TABLE 2 - T-300/5208 GRAPHITE/EPOXY IMPACT TESTS

Specimen (in)	Drop Height (ft)	Ball Dia (in)	Weight (lb)	Impact Energy (ft-lb)	Observation
1/4 x 3 x 6	4.5	4.5	13.43	60.5	Optical fiber failed in 3-in. direction only at impact site (tensile surface). Panel had minimum fiber breakage and delamination on tensile surface. Compression surface shows no visible damage.
1/4 x 3 x 6	5.5	4.5	13.43	73.9	Optical fibers in both directions (tensile surface) failed at impact site. Panel cracked, fiber failure across entire 3-in. section.
1/4 x 3 x 6	6.5	4.5	13.43	87.3	Catastrophic panel failure. Some optical fibers pulled out, others failed at failure site.
1/4 x 3 x 6	5.5	4.5	13.43	73.9	All optical fibers (tensile surface) failed in 6-in. direction. Panel severely cracked on tensile surface, extensive delaminatio
1/4 x 3 x 6	5.5	4.5	13.43	73.9	Optical fibers failed (tensile surface) but not directly on impa site. Panel fiber failure on tensile side, gross delaminations, no visible damage on compression surface.

FUTURE WORK

Future areas requiring investigation include optical fiber selection and optimization, appropriate fiber spacing for particular loading and structures, emitter and detector selection and interfacing instrumentation.

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